Borkum Riffgrund

forces, run-up and scour protection

Larsen, Brian Juul; De Vos, Leen; Frigaard, Peter; Andersen, Thomas Lykke

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Forces, Run-up, Scour and Scour Protection

Brian Juul Larsen[(1)], Leen De Vos[(2)], Peter Frigaard[(1)] and Thomas Lykke Andersen[(1)].

(1) Aalborg University, Sohngaardsholmsvej 57, DK-9000 Aalborg, Peter.Frigaard@civil.aau.dk
(2) Ghent University, Technologiepark 904, B-9052 Zwijnaarde, Leen.DeVos@UGent.be

Introduction

When building an offshore windfarm, a lot of issues have to be dealt with. The wind turbines are placed in a hostile environment and they often have to withstand storm-force waves and tidal currents. The waves lead both to significant impacts/forces on the tower and to wave run-up on the tower. In addition, the turbine towers have to remain stable on a sea-bed that may be continuously changing.
While the wave forces on and scour around a monopile foundation are relatively well known, other foundations may be better suited to withstand the conditions for a specific site. For these other structures, e.g. gravity based structures, the flow situation becomes very complex and model tests are often indispensable to assess the influence of the structure's presence in the flow.
Plans to develop and construct an offshore wind farm on Borkum Riffgrund, located on the German side of the North Sea, were made by the joint-venture of Energi E2 and Plambeck Neue Energien AG. This paper describes the model tests that were carried out by Aalborg University for the Borkum Riffgrund offshore wind farm project. The tests involve force measurements, run-up tests, scour measurements and scour protection tests on different windturbine foundations. The results show a significant influence of the foundation type on both wave forces and scour.

Experimental Set-up

The tests are conducted in one of Aalborg University's wave flumes with a length of 30 m, a width of 1.5 m and a depth of 1 m. The tests are performed with a length scale of 1:50 and values are scaled according to Froudes law. JONSWAP spectra with a peak enhancement factor, γ, of 3.3 are used for all tests. The water level at the model varies between 0.5m and 0.64m (25 and 32m in prototype). The elevation signal is measured both in front of the wave paddle and beside the model. In both places three gauges are mounted to separate the incoming and reflected waves by means of the method by Mansard and Funke [1].
For the tests on wave forces and wave run-up, a piston-type wave paddle generates the waves at one end of the wave flume, where an absorbing beach is installed at the other end. The models are built in in front of the absorbing beach. A sketch of the model set-up is shown in Fig.1.

Figure 1. Model set-up for tests on wave forces and wave run-up

For the scour and the scour protection tests, currents become important, so a closed pump circuit was built in to create currents going along with the waves (Fig. 2).

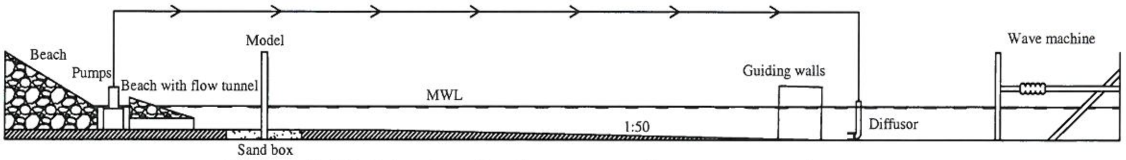


Figure 2. Model set-up for the scour and scour protection tests

In total four different models are tested, a monopile, a steel tripod, a concrete tripod and a cone foundation (Fig. 3). The measurements on the monopile foundation are used as a reference.

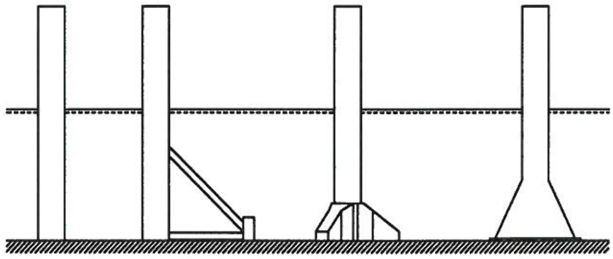


Figure 3. Models: Monopile Steel tripod Concrete tripod Cone

Wave Forces

When designing an offshore wind turbine, maximum forces on and maximum moments at the bottom of the pile are important. 3 models were tested, to investigate the influence of the foundation type. The cone foundation was not tested. Some pictures that were taken during the tests are shown in Fig. 4.

Figure 4: pictures of different set-ups

Fig. 5 shows the variation of measured forces in function of wave height, for all three structures (results are given in prototype values). The graphs show that the forces are proportional to the wave heights, indicating inertia dominated structures.

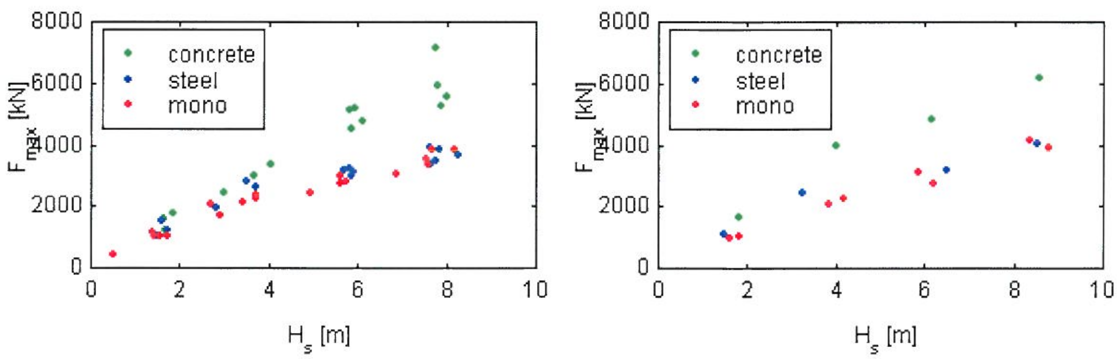
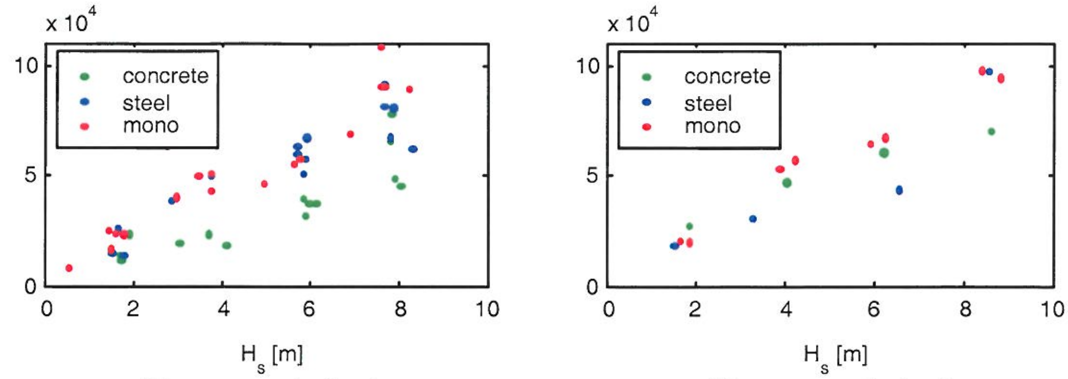


Figure 5: (prototype values) 25 m mean water level 32 m mean water level

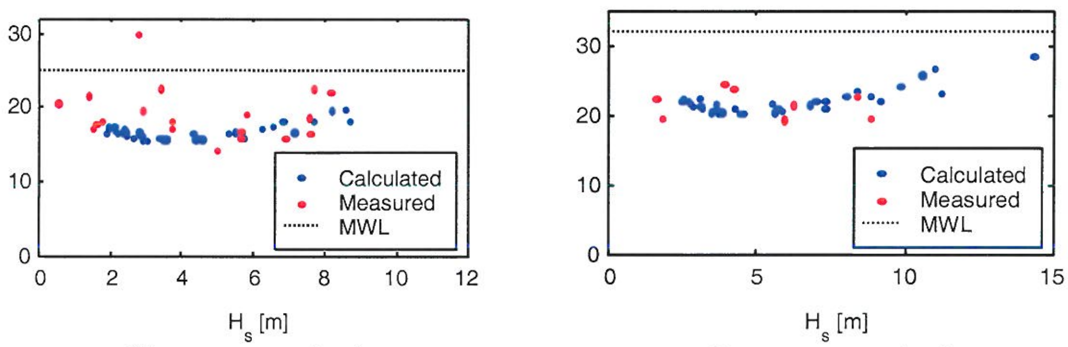
Fig. 6 shows the variation of measured moment at the sea bottom in function of wave height, for all three structures.



25 m mean water level **32 m mean water level**

Figure 6: Maximum horizontal monent [kNm] as function of significant wave heigth (prototype values)

In Fig. 7 the vertical point of attack from the monopile tests has been compared to some Boussinesq simulations. The vertical point of attack from the measured results is related to the largest positive force measured in each test (F_{max}). Fig. 7 shows the bigger tendency to wave breaking at 25 meters during the model testing.



25 m mean water level **32 m mean water level**

Figure 7: Vertical attack point [m] of largest positive force (prototype values).

Run-up

Observations at the Horns Rev windfarm show that run-up levels are much higher than expected or accounted for in the design, causing damage at the boat landing facilities and the wind turbine's platform. It is known that the direction of the incoming waves is important concerning the run-up distribution along the pile. This makes it possible to determine an optimal location for the boat landing facilities and entrance door. Therefore it is important to have an insight in both the maximum run-up level and the distribution of the run-up along the pile, both of which are investigated here.

Some results of a first small-scale experimental study are shown. Only the run-up on the monopile foundation is measured. Both regular and random waves are generated.

6 resistance-type wave gauges are mounted on the model to measure the wave run-up and to determine the variation of the run-up around the pile. Marking tapes are placed with a distance of 0.02 m and video recordings are made to allow visual inspection of the recorded run-up measurements. Fig. 8 shows the position of the wave gauges whereas Fig. 9 shows a picture of the mounted wave gauges.

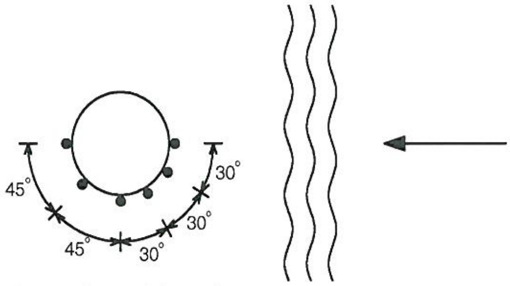


Figure 8: position of run-up gauges

Figure 9: Picture of mounted capacitance wave gauges on both models

Figure 10: work in progress

Fig. 11 plots the run-up as a function of significant wave height, showing that there is an exponential increase of the run-up, when the wave height increases.

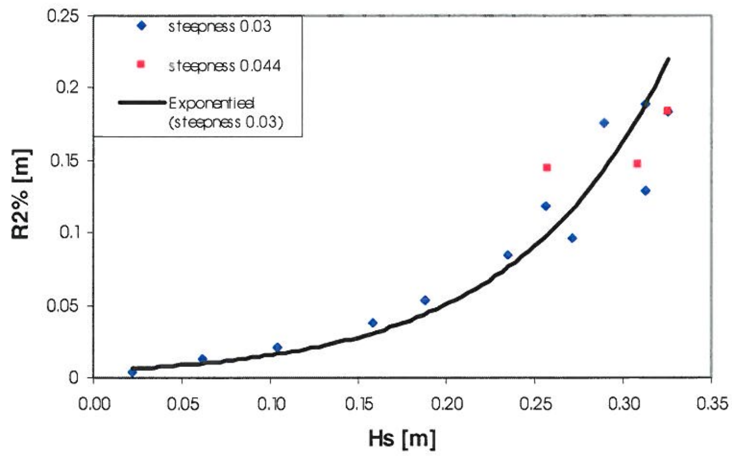


Figure 11: $R_{2\%}$ as a function of wave height for two different wave steepnesses

The variation of the run-up around the pile was measured for three different wave heights (approximately H_s = 0.13, 0.15 and 0.16 m) and two different steepnesses (approximately 0.03 and 0.044). Fig. 12 shows the measured $R_{2\%}$ value, relative to the $R_{2\%}$ value at the front side of the pile.

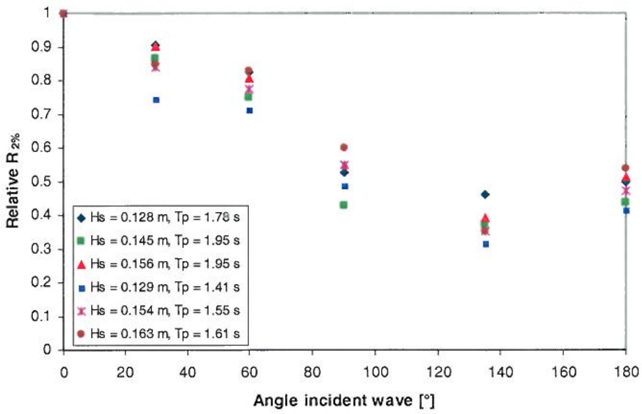


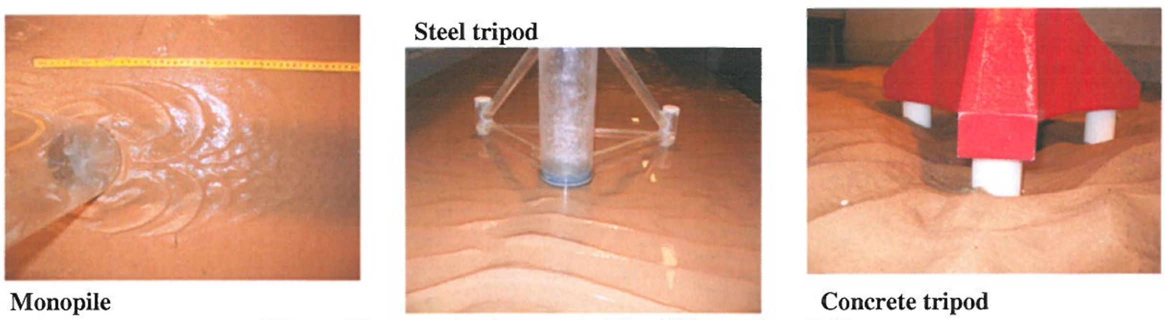
Figure 12: Relative $R_{2\%}$ along the pile

As expected the maximum run-up is found at the front side of the pile. The figure shows that the lowest run-up is not located on the leeside but at an angle of approximately 135°. The position with the lowest run-up gives approximately 40% of the maximum run-up.

These tests are only a first set of experiments. To be able to design the platform, information on run-up velocities and run-up forces on the platform are necessary. Further more, as mentioned before, offshore farms are placed under very different conditions and the monopile is not always the optimal foundation. In deeper water conditions, gravity based structures might be better suited. It is reasonable to assume that the run-up will be influenced by the shape of the foundation. This is investigated in a later test series.

Scour and Scour Protection

When a wind turbine is placed offshore and no countermeasures are taken, the sea bottom is subject to local scour due to waves and/or currents. Although there has recently been research on scour around monopiles [2] [3], the size and extend of the scour holes of other foundations is not well known. Often, the expected scour depth is not acceptable for the structure and the application of scour protection is necessary. There are little good guidelines available to design scour protections, in particular not for wave-current combinations and for foundations differing from a monopile.
The same three structures as for the force tests were tested for scour. Both depth and extension of the scour holes are measured. Although it is difficult to make a direct link between the dimensions of the scour and the necessary scour protections, one can say that scour protections are recommended once the scour depth becomes significant.
Fig. 13 shows some pictures of scour development at the three different structures.



Steel tripod

Monopile

Concrete tripod

Figure 13: scour development at the different foundations

Fig. 14 shows the comparison of the measured scour depths with the expressions, proposed by Sumer and Fredsoe [2] for monopiles. The scour depth relative to the pile diameter is presented. For all structures, the diameter of the main pile is used. In the scour tests, KC numbers of 2.5 till 10.5

where tested. From this figure it can be seen that scour is larger for both the steel tripod and the concrete tripod, while it is largest for the concrete tripod.

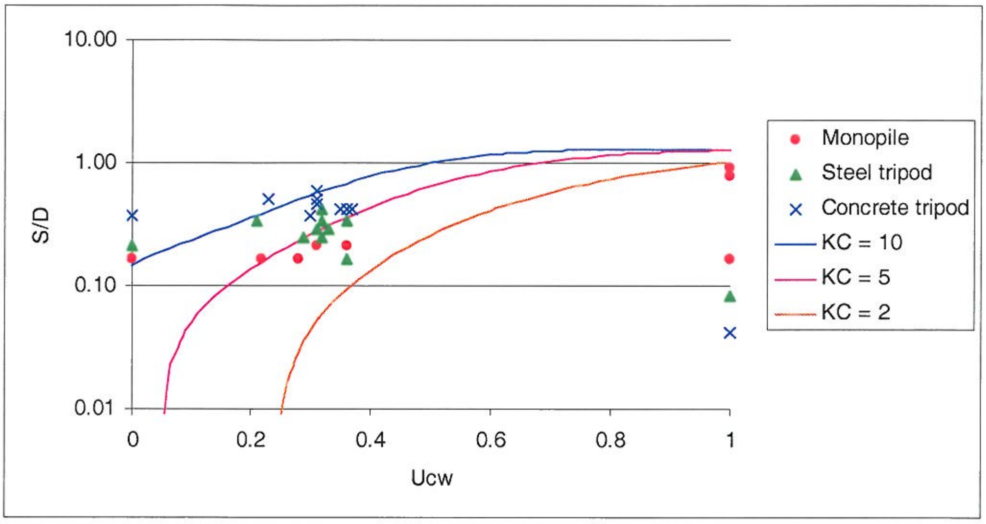
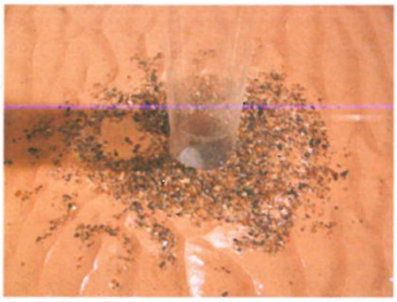


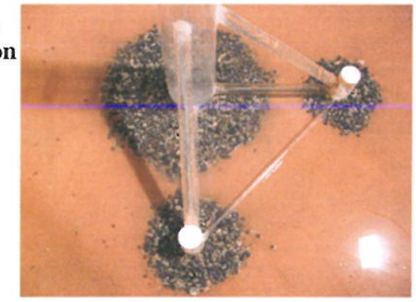
Figure 14: Test results compared to curves based on expressions by Sumer and Fredsøe [1]. The scour depth for current alone (U_{cw} = 1) will converge to S_c/D = 1.3.

For the scour protection tests, all four structures were tested with three different sizes of scour protection material, with d_{50} respectively equal to 1.78 mm, 5.16 mm and 5.8 mm.
Pictures of the different foundations with scour protection are shown in Fig. 15.

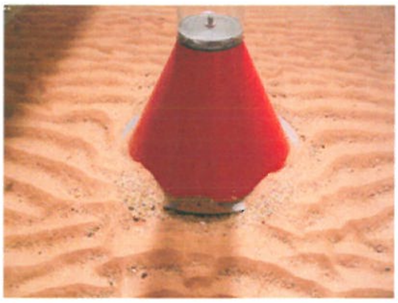
a) monopile, scour protection after severe storm



b) steel tripod, scour protection before testing



c) conctrete tripod scour protection before testing



d) cone, scour protection after severe

Figure 15: pictures of scour protections around all different foundations

In comparison with the monopile, damage to the scour protection was somewhat larger for the steel tripod and the concrete tripod for the same environmental conditions. Damage was smallest for cone foundation.

Conclusion

When designing an offshore windfarm, several aspects have to be taken into account and model tests are often indispensable. For the design of the Borkum Riffgrund offshore windfarm, four different foundation types are considered, a monopile, a steel tripod, a concrete tripod and a cone foundation. Small scale model tests are performed by Aalborg University (Denmark) to estimate the wave forces, wave run-up, scour and scour protection for the specific conditions of the Borkum Riffgrund site.

The model tests show a significant influence of the foundation type on both wave forces and scour. Both maximum forces and scour are largest for the concrete tripod. Maximum moments are however smaller for the concrete tripod. Considering the scour protection, damage is smallest for the cone foundation. The run-up tests indicate that maximum run-up levels increase exponentially with increasing wave height. The run-up distribution along the pile shows a maximum run-up at the front side of the pile and a lowest run-up at 135°. The position with the lowest run-up gives approximately 40% of the maximum run-up.

References

[1] Mansard E.P.D., Sand S.E. & Funke E.R., "*Reflection analysis of non-linear Regular* Waves", National Research Council of Canada, Hydraulics Laboratory, Technical Report TR-HY-011, 1985

[2] Sumer B.M and Fredsoe J. "*The mechanics of scour in the marine environment*", World Scientific, 2002

[3] Whitehouse R. "*Scour at marine structures*", Thomas Telford, 1998